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SPACE SIMULATION GAUGES

By

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ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

NOTICES

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FOREWORD

This report summarizes the results of a theoretical study of adapting ion gauges to measure the incidence gas pattern on a vehicle in a test chamber.

The research was conducted by Aero Vac Corporation, Green Island (Troy), New York, for the General Electric Company, Schenectady, New York, under Contract No. AF 40(600)-954 with the Arnold Engineering Development Center.

ABSTRACT

This report discusses two types of Space Simulation Ion Gauges designed for measurement of vacuum level in aerospace environmental test chambers. These gauges indicate the incidence rate of background gas molecules impinging on the vehicle under test even though the gauges are remote from the vehicle surface and attached to the wall of the test chamber.

The Type 1 gauge incorporates a cryogenically-cooled condensing surface within the gauge to compensate for pumping effects of the cryogenically-cooled pumping panels in the simulator. With proper design, matching the chamber properties, the gauge reads directly the incident flux on the vehicle. The Type 2 gauge measures the pattern of gas emission from the wall. From these data the gas incidence pattern on the vehicle can be calculated.

The report describes the need for Space Simulation Gauges, the operation of each type, and their advantages and limitations.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

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ILLUSTRATIONS

NOMENCLATURE

a	area, a variable
A	a constant dependent on configuration of chamber pumping surfaces
A_1, A_2, A_3	areas
A_O	area of mouth of gauge
A_S	surface area of sensing zone of gauge
A_P	area of pumping surface in gauge
A_T	total surface area of gauge shell including mouth area
F	gas emission rate in molecules per unit area per unit time
k	dimensionless distance from center of chamber to baffle or gauge mouth $= \frac{r}{R}$
m	dimensionless distance from chamber wall to baffle or gauge mouth $= \frac{R-r}{R}$
O	a point
P	probability
r	distance from baffle or gauge mouth to center of chamber
R	radius of chamber
R_1, R_2, R_3, R_4	gauge readings
S	gauge sensitivity, reading per molecule incident on the sensing zone per unit time
α	condensation (sticking) coefficient
β	an angle
β_B	angle subtended by baffle
θ	an angle
ϕ	gas incidence rate, molecules per unit area per unit time

1.0 INTRODUCTION

In most vacuum systems of the past the total amount of the chamber wall which was acting as a pump was sufficiently small that one could consider that random gas flow existed everywhere in the chamber except at the throat of the pump itself. In modern space simulators large quantities of cryogenic pumping are used, resulting in vacuum chambers in which a great deal of the wall is acting as a pump. This pumping effect creates the condition of a highly directional gas flow from the test item to the chamber wall. This characteristic is particularly true of water vapor outgassing being condensed on liquid nitrogen-cooled walls. One problem created by this highly directional gas flow is that of measuring the pressures which exist.

Even though there is no direct relationship between the pressure measured at the test vehicle and various levels of altitude (due to the difference in gas type and energy), it is still desirable to have an indication of the incidence pressure or molecular flux on the vehicle, particularly when we consider that the molecular flux may vary by several decades over the surface of the vehicle.[1] Three important problems must be solved in order to determine the vacuum level of simulation achieved: (1) What does an ion gauge read in terms of the gas properties in the test region? (2) What type of gauge should be used for space simulators? (3) Where should the gauges be located?

The answer to the first question was covered in a previous report on this project[2] in which it was shown that a tubulated gauge reads in proportion to the molecular flux incident on the end of the tubulation, while a nude type gauge reads the molecular density in the test region. As a result, if one is interested in measuring the rate at which molecules are bombarding the surface of the vehicle, some form of tubulated or restricted entrance gauge should be used.

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1. AEDC-TDR-63-88. "Molecular Flux Distribution in an Aerospace Chamber," C. A. Tsonis.
2. AEDC-TDR-63-37. "Ion Gauge Characteristics in an Aerospace Chamber Simulator," D. H. Holkeboer.

As far as gauge location is concerned, it is apparent that since the desired measurement is the flux on the vehicle, vehicle-mounted gauges are desired. This mounting location, however, has several drawbacks. First, there are problems of electrical connections from the amplifier to the sensing elements. Not only may these leads be quite long, but they may also have to be capable of rotation with the vehicle rotation. Both of these factors create serious problems of electrical pickup and high noise level in ion current measurements. In many vehicles there may not be available mounting locations for the gauges which are desired. In addition, the presence of the gauge may interfere with the thermal balance of the test item or conversely, the test item or sun may result in changes of the ion gauge temperature and corresponding variations in calibration. For these reasons a wall-mounted gauge would appear more practical. The major problem in this regard is how to make a wall-mounted gauge read the same as if it were mounted on the test vehicle. For the purpose of this report, any wall-mounted gauge or combination of gauges capable of interpretation at the vehicle surface is referred to as a Space Simulation ion gauge (abbreviated S.S.).

The problem then becomes determining the type of tubulated wall-mounted gauge to be used to measure the molecular flux incident on the test vehicle and determining the number and exact location of gauges. This report is concerned with this specific problem as a part of a broad molecular kinetics study. Two different types of S.S. gauges will be discussed and their relative advantages and disadvantages will be considered. The first type, a pumping type gauge, was originally developed at and for the General Electric Co. In essence, this gauge uses localized cryogenic pumping within the envelope of the gauge in order to obtain a controlled reduction in pressure reading for condensible types of gas. The second S.S. gauge to be discussed is a conventional type of gauge mounted to receive gas from a limited area of the wall. Its capability as an S.S. gauge stems from knowing the probability equations for gas flow from different parts of the chamber wall to the test item. A plurality of such gauges are used, and their readings combined in a particular mathematical fashion such that molecular fluxes on the vehicle may be computed within a reasonable degree of accuracy.

2.0 TYPE 1 GAUGE

2.1 DESCRIPTION

This type of Space Simulation Gauge consists of a conventional ionization gauge modified as shown in Figure 1. The sensing element is identical to a conventional inverted Bayard-Alpert gauge while modifications have been made in the gauge envelope. In particular, the gauge envelope is designed to be cooled by liquid nitrogen, and in fact, it is part of a liquid nitrogen-cooled pumping panel in the space simulator.

2.2 PRINCIPLE OF OPERATION

The gauge is intended to indicate the gas flux incident on the vehicle under test in a space simulation chamber even though the measurement is made at the chamber wall. The method used to create this gauge behavior is valid if certain initial assumptions are made:

1. Outgassing of the vehicle is strongly predominant as the gas source in the chamber, and this outgassing is uniformly distributed over the vehicle surface.

2. The outgassing consists entirely of species which are either non-condensible or strongly condensible on the pumping surface.

3. The directional pressure effect for condensible gases is known in terms of ratios from basic design parameters of the chamber.

The operation of the gauge is best explained by describing first the behavior of a completely conventional tubulated gauge and then considering the effect of the pumping surfaces on the gauge behavior.

In a conventional tubulated gauge operated at a given set of electrode voltages and a given electron current the reading is dependent on the gas type and is proportional to the number density of molecules in the ionizing zone of the gauge. In this discussion we wish to neglect the dependence of readings on gas type, and consider only the effects of number density. Referring to the sketch in Figure 2, it will be assumed that molecules are incident on the mouth of the gauge "A_o" in a random manner and with an incidence rate of "ϕ" molecules per unit area per unit time. It is further assumed that the reading of the gauge is proportional with some constant "S" to the incidence rate of molecules on the boundaries of the ionization region or "sensing zone" of the gauge. Finally, it is assumed that the gauge is approximately spherical so that gas leaving any wall area inside the gauge becomes uniformly distributed over the gauge wall on first incidence. If the flow of gas in the gauge is random, the gas incidence rate is the same on all surfaces within the gauge including the exit hole.

Let ϕ = the incident flux entering the gauge.

ϕ_G = the incident flux on surfaces within the gauge.

The number of molecules entering the gauge per unit time is equal to the number of molecules leaving the gauge per unit time;

$$\phi\ A_O = \phi_G\ A_O,\ \text{so that}\ \phi_G = \phi. \tag{1}$$

The number of molecules incident on the sensing zone is then

$$\phi_G\ A_S = \phi\ A_S \tag{2}$$

The corresponding reading of the gauge is

$$R_1 = S\ A_S\ \phi. \tag{3}$$

where S = a proportionality constant. The significance of this discussion will become apparent when these results are used in a subsequent section.

Consider next a simple type of space simulation gauge incorporating a cooled pumping area such as shown in Figure 3. It is again assumed that the gas flow is essentially random inside the gauge. This assumption is a reasonable approximation since the pumping area is about one sixth of the total wall area, and consequently, only one sixth of the molecular trajectories lead to the removal of a molecule from the gauge by pumping.

The rate of removal of molecules is again equal to the rate of supply

$$\phi\ A_O = \phi_G\ (A_O + \alpha\ A_P) \tag{4}$$

where α is the condensation coefficient of the pumping surface.

The reading of the gauge is

$$R_2 = S\ A_S\ \phi_G = S\ A_S\ \phi\ \frac{A_O}{A_O + \alpha\ A_P} \tag{5}$$

In other terms:

$$\frac{R_2}{R_1} = \frac{A_O}{A_O + \alpha A_P} \tag{6}$$

where R_1 = the reading of a conventional non-pumping gauge. This reading is that for a single gas species. In the case where a mixture of gases are present, each gas acts independently according to its incident rate "ϕ" and condensation coefficient "a." The gauge reading is the sum of the contributions of the individual gases.

This type of gauge permits a designer to choose values of "A_O" and "A_P" to alter the response to condensible gases by a selected factor to compensate for pumping effects in the chamber. In the space simulator, the flux of any given gas species leaving the chamber wall under an incident flux "ϕ" is

$$\frac{F}{\phi} = (1-\alpha A) \tag{7}$$

where A is the fraction of the surface covered by pumping panels. The proper operation of this particular type of gauge is secured when $\frac{R}{R_1}$ is equal to $\frac{F}{\phi}$ so that

$$\frac{A_O}{A_O + \alpha A_P} = (1-\alpha A) \tag{8}$$

for all gas species separately. Note that this condition is automatically achieved for non-condensible gases ($\alpha = 0$). For condensible gases, one will ordinarily assume that α is nearly one and choose values of "A_O" and "A_P" such that

$$\frac{A_O}{A_O + A_P} = 1-A \tag{9}$$

Then

$$\frac{R_2}{R_1} = 1- \frac{\alpha A}{1-(1-\alpha)A} \tag{10}$$

By comparing "equation (10)" with "equation (8)," it is seen that the denominator of the second term in "equation (10)" represents a departure from the desired behavior. This departure will not occur when α is either 0 or 1, but will exist for intermediate values of α. If the value of α is known, the gauge can be designed for this value to eliminate the error. This relatively simple type of gauge exhibits the type of behavior desired in a space simulation gauge; that is, it compensates for pumping effects in the chamber provided the initial assumptions are met. For secondary reasons, however, modifications in the construction are desirable. One reason for modifying the configuration is to reduce the background gauge reading resulting from the outgassing of the uncooled parts of the gauge envelope itself. In the space simulation chamber proper, the relationship of pumping area to outgassing area is very large resulting in very low pressures. In the gauge described above, the outgassing surface area is about five times as great as the pumping area resulting in an internal pressure which may be comparable to or higher than that in the chamber. The outgassing of stainless steel may be estimated at 10^{-7} Torr-liters/sec-cm^2 after a period of a couple of hours under vacuum. With a pumping speed of 15 liters/sec-cm^2 for water vapor (the predominant outgassing constituent) the pressure can be calculated:

$$P = \frac{5 \times 10^{-7}}{15} = 3 \times 10^{-8} \text{ Torr} \qquad (11)$$

To improve the background level, consider a gauge constructed as shown in Figure 4. The response of this gauge to condensible gas can be analyzed by noting first of all that in the conventional non-pumping gauge the total number of molecules incident on the sensing zone per unit time is related to the total number of molecules leaving the gauge walls per unit time by a simple area ratio

$$\frac{\phi_G \, A_S}{\phi_G \, A_T} = \frac{A_S}{A_T} \qquad (12)$$

where A_T = the total wall area of the gauge including the hole.

Here again, assuming that the gauge is approximately spherical, the uniform distribution property is used. In the pumping gauge depicted in Figure 4, the sensing zone is subjected to a very similar pattern of molecular flux totalling ϕA_O but originating from a limited area only, that is, from the entrance hole. Then

$$R_3 = \phi A_O \left(\frac{A_S}{A_T}\right) S = R_1 \frac{A_O}{A_T} \tag{13}$$

"Equation (13)" is correct only if the condensation coefficient of the pumping surfaces is unity. For $\alpha < 1$ it is necessary to add correction terms to "equation (13)." The first of these terms is derived by considering the flux through the hole to be distributed on the wall and a fraction $1-\alpha$ of this flux to be re-emitted from the walls of the gauge and incident upon the sensing zone. This term is

$$\frac{\phi A_O}{A_T} (1-\alpha) \frac{A_P}{A_T} A_S S \tag{14}$$

Additional terms are derived in a similar manner considering multiple bounces in the gauge. The complete equation is then

$$\begin{aligned} R_3 &= R_1 \left[\frac{A_O}{A_T} + (1-\alpha) \frac{A_O}{A_T}\frac{A_P}{A_T} + (1-\alpha)^2 \frac{A_O}{A_T}\left(\frac{A_P}{A_T}\right)^2 + \text{--}\right] \\ &= R_1 \frac{A_O}{A_T} \frac{1}{1-(1-\alpha)\frac{A_P}{A_T}} \end{aligned} \tag{15}$$

Here again the response of the gauge to condensible gases can be controlled by the choice of "A_O" and "A_T" in the initial design. (Note that "A_P" is determined when "A_O" and "A_T" have been chosen.) The designer will attempt to choose values of "A_O" and "A_T" such that the ratio $\frac{R_3}{R_1}$ is equal to the ratio of directional fluxes $\frac{F}{\phi}$ given by "equation (7)." Since the magnitude of α is unknown, the gauge would normally be constructed so that $\alpha = 1$. Hence

$$\frac{A_O}{A_T} = 1-A \tag{16}$$

where A is the factor in "equation (7)" above. "Equation (15)" then reduces to

$$R_3 = R_1 \left(1 - \frac{\alpha A}{1-(1-\alpha)A}\right) \tag{17}$$

Thus the behavior of the gauge deviates from the desired behavior when α is an intermediate value between zero and one. Moreover, reference to "equation (10)" will show that the deviation from ideal behavior is exactly the same for this gauge and for the basic pumping gauge described above.

A practical gauge construction is likely to be similar to the sketch in Figure 1. Here the gauge shell is partially formed by an extension of the liquid nitrogen-cooled liner of the space simulation chamber. The base on which the gauge sensing element is mounted is an extension attached to the wall of the vacuum chamber and is uncooled. The behavior of such a gauge can be analyzed in a manner similar to the preceding. Consider Figure 5 and assume that the gauge behaves as if spherical. The reading of the gauge for each gas species can be expressed in a series similar to "equation (15)." The first term of the series again represents that portion of the reading due to direct incidence of the incoming flux on the sensing element and is identical to the first term in "equation (15)." Subsequent terms indicate the portion of the reading due to successive bounces of the molecules inside the gauge. In this case, the multiplying factor in these terms differs from that in "equation (15)" because of the bouncing from the uncooled portion of the wall. This multiplying factor is

$$\frac{(1-\alpha)A_P}{A_T} + \frac{A_T-A_P-A_O}{A_T} \tag{18}$$

The reading of the gauge then becomes

$$R_4 = R_1 \frac{A_O}{A_T} \left[\frac{1}{1 - \frac{(1-\alpha)A_P}{A_T} - \frac{A_T-A_P-A_O}{A_T}}\right] \tag{19}$$

On the assumption that α is either zero or close to one for all gases expected, the gauge should be designed so that

$$\frac{A_O}{A_P} = 1-A \tag{20}$$

again referring to "equation (7)." Under this condition, "equation (19)" reduces to

$$R_4 = R_1 \left(1 - \frac{\alpha A}{1-(1-\alpha)A}\right) \tag{21}$$

which is exactly the same expression that was found in "equation (10) and (17)." That is, the behavior of the gauge is once again the same as in the preceding cases.

Thus all three of these types of space simulation gauges operate in a basically similar manner. The differences between them are in respect to their inherent background levels due to outgassing within the gauge and in the mechanical convenience of gauge construction and incorporation in a space simulation chamber. Of course, the hole size will also be different, all other things being equal. In particular, the merits of the fully pumping gauge in comparison to the gauge with the non-cooled base plate relate almost entirely to the ease of construction and accessibility for maintenance. The fully pumping gauge has an advantage in that it can be an attachment to a chamber pumping panel but will not suffer changes in behavior if appreciable motion of the panels occurs. The gauge with warm base plate, on the other hand, has an advantage of being easily removable from outside the chamber if repairs to the sensing element are necessary. A discussion of the advantages and limitations of the Type 1 gauge is presented in a subsequent section.

2.3 EXPERIMENTAL TESTS

In order to test the principle of the pumping type space simulator gauge, two standard ion gauges were modified to correspond to the basic pumping type gauge discussed above. These two gauges were fitted with open end shells and a movable end plate was constructed. The end plate was cooled by liquid nitrogen and had a hole for gas emission to the gauge. The end plate and one gauge are shown in Figure 6. The end plate was supported so that it could be positioned in front of either gauge and the hole in the plate could be moved with respect to the remainder of the gauge. These adjustments could be made with the system under vacuum. The size of the hole was chosen to allow a gas emission area equal to one tenth of the gas removal area. That is, the factor A was chosen to be 0.9.

Water vapor was used as the test gas in this experiment, and the pumping surface was cooled with liquid nitrogen. Water was introduced through a conventional leak at its saturation pressure corresponding to room temperature. Because the tests were run in the course of about 1 hr, the pressure of the water vapor was not monitored, but the temperature of the room was observed to remain within 1°C during this period, assuring that vapor pressure of the water was constant during the experiment.

The directionality of flow found in a space simulator was not simulated in this experiment; the flow was essentially random. This course was followed because the directionality of flow is not essential to the operation of the gauge. The gauge is intended merely to register only 10% of the condensible gas incident on it, as if this gas were incident upon a space simulator wall where 90% was pumped and 10% reflected back to the vehicle under test.

The results obtained with water vapor are shown in Figure 7. In the two gauges, the pumping surfaces reduced the gauge reading by factors of 10.3 and 9.8, respectively, versus a calculated value of 10.2 based on the actual dimensions of the gauge. In addition, the gauge reading was sensitive to the position of the hole relative to the gauge element. The center position of the hole corresponds most closely to the spherical characteristics assumed in the preceding analysis. The reading was highest with the hole in the center and decreased 15% to 20% as the hole was moved over to the point of tangency with the gauge shell. In the figure shown, the further decrease in the readings with additional shifting of the hole results from the hole being only partially exposed to the gauge. The rapid rise at the extremes of the traverse indicates that the end of the gauge is no longer fully covered by the cold plate at these points.

The change in readings as the hole is shifted evidently reflects a non-uniformity of distribution due to the pumping action of the gauge. It is suggested that with the hole in the center of the gauge and with random gas incidence on the hole, the incoming molecules are distributed fairly uniformly over the inside of the gauge. These molecules bounce around an average of six times before being condensed on the cold plate or escaping from the gauge, thus contributing a certain gas density within the gauge. When the hole is moved close to the side walls of the gauge, the molecular distribution is no longer uniform, more molecules hitting the side wall of the gauge near the orifice than elsewhere. These molecules have a somewhat higher probability of escaping or being pumped than those farther from the cold plate, and the average density of the gas in the gauge is therefore lower.

2.4 APPLICATIONS OF THE PUMPING TYPE GAUGE

The pumping type space simulation gauge has application in some but not all space simulation chambers. Under conditions when it can be applied, it offers a fairly simple installation and has an inherently low background reading in the face of internal outgassing of the gauge itself. It also has the advantage that its behavior is not a function of the shape of the space simulation chamber or of the shape and size of the test vehicle. The pumping type gauge has certain limitations which prevent its use in space simulators in that it does not indicate a gas load on the vehicle originating from outgassing of a component on the wall such as a solar simulation mirror for example. That is, the gauge reads correctly only if the vehicle outgassing is the predominant gas source. In fact, the vehicle outgassing reflected by the pumping wall of the space simulator must be the predominant source of gas incident on the vehicle in order for the gauge to indicate correctly. In addition, the gauge reading is properly developed only when the pumping coefficient is close to zero or to one. This condition will probably occur in most cases and it may be possible to design the gauge to minimize or eliminate this error if the pumping coefficient is known. A third limitation of the pumping type gauge is its directional properties. While it was assumed in the analysis that the gas incidence on the gauge mouth was random, most of the reading is produced by those molecules which pass through the mouth of the gauge in such a manner that they are directly incident on the sensing element. Thus the gauge senses mainly those sources of outgassing which are directly in front of it and has very little sensitivity to gas sources far off the center line.

It should also be born in mind that gauges of this type show a temperature effect on non-condensible gases. This temperature effect arises from thermal transpiration between the gauge and the vacuum chamber. The effect exists because non-condensible molecules entering the gauge make several bounces before escaping. During the time that a molecule remains in the gauge, it makes several incidences on the cold pumping surface and assumes a low temperature. Condensible molecules in the same gauge are nearly always pumped upon striking a cold surface so that very few cold molecules are incident upon the sensing element. The ratio here will depend on the pumping coefficient and relative size of the gauge mouth. The reduced temperature of the non-condensible molecules is reflected in a lower velocity, and, consequently, each molecule remains within the sensing zone for a longer time and thus has a higher probability of being ionized and producing a reading. The magnitude of the temperature effect is inversely proportional to the square root of the temperature of the molecule. In the completely pumping gauge, it may be safely assumed that the non-condensible molecules reach the temperature of the pumping surface. When the gauge includes an uncooled base plate, the temperature of the molecules can be estimated by comparing the areas of cold and warm surface.

3.0 TYPE 2 SPACE SIMULATION GAUGE

3.1 DESCRIPTION

The Type 2 gauge has the same purpose as Type 1: namely, to indicate the gas incidence on the vehicle from measurements made at the chamber wall. The Type 2 gauge uses a different approach to the problem than Type 1 in order to overcome some limitations discussed above.

The basic approach is to measure, with a suitable number of properly located gauges, the pattern of gas flux emitted from the wall whether due to outgassing, leaks, or reflection of molecules originating from other sources and incident on the wall. After measurements are made the incident flux pattern on the vehicle is computed mathematically. This computation will make use of the mathematical analysis of gas distribution in a space simulation chamber reported by C. Tsonis.[1] A discussion of how this computation may be made is presented in the section on APPLICATION below. For present purposes, it will be assumed that the computation can be performed if the proper data are obtained by gauge measurements.

Each gauge, then, is intended to measure the total emission of gas molecules per unit area per unit time from a limited zone on the chamber wall. Ideally, the gauge reading should indicate an average of the emitted flux over the wall area viewed, but in practice, this uniform sensitivity is difficult to achieve. Since the gauge is intended to measure flux rather than density, it should be tubulated or enclosed in a shell of known temperature rather than a nude gauge.

One way in which a Type 2 Space Simulation Gauge can be constructed is to simply mount a conventional tubulated ion gauge on a support extending from the chamber wall which permits it to face the wall and view the desired area. This construction has some practical disadvantages, however. First, access to the gauge for repairs or replacement is difficult. In addition, in a large simulator the gauge may have to be 10 ft to 15 ft from the wall in order to view a

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1. AEDC-TDR-63-88. "Molecular Flux Distribution in an Aerospace Chamber," C. A. Tsonis.

reasonably sized area because of the inherent 180° viewing angle of a simple tubulated gauge. Some of these practical problems can be overcome by other configurations.

One of several possible arrangements is shown schematically in Figure 8. Just as in the Type 1 gauge, the sensing element is located inside the tubulated enclosure marked gauge. The desired behavior in this case is achieved with the aid of the baffle over the mouth of the gauge to control the angle of view. The construction incorporating a baffle has two advantages: (1) it places the gauge head in a position more easily accessible from outside the vacuum chamber in case repairs or replacement is required, and (2) it permits an angle of view greater than 180° so that the distance that the gauge extends into the vacuum chamber can be reduced.

It should be noted that the configuration represented here is not limited to pressure gauges. A similar type of mounting for a mass spectrometer gas analyzer will enable the spectrometer tube to be mounted in an accessible position while simultaneously obtaining a sample of the gas components from the population of molecules directed toward the vehicle. In this way, the composition determined by the mass spectrometer will be that of the gas background incident on the vehicle.

3.2 OPERATION OF THE TYPE 2 GAUGE

The operation of the gauge can be understood by considering first its behavior when the emission of gas from the wall is uniform over the zone viewed by the gauge. Subsequently, non-uniformities in gas emission will be considered. Before examining the behavior of the gauge, it is necessary to state an important law relating to molecular flow and the cosine distribution. This proposition can be explained by reference to Figure 9. The proposition is stated as follows: The incident flux on a small area of surface dA_1 due to emission of gas at a rate "F" per unit area from surface dA_2 is the same as the incidence rate observed when dA_2 is replaced by any other arbitrary surface dA_3 occupying the identical solid angle and having the same gas emission rate per unit area "F." This proposition means that, in order to calculate the incidence rate on area dA_1 due to gas emission from dA_2, we may choose any convenient area occupying the same solid angle as dA_2 and having the same gas emission per unit area. This proposition is an established law and therefore a proof is not included in this report.

A second proposition will also be stated without proof: If a small area is centered in a hemisphere which is emitting gas at a rate "F" per unit area over its entire surface, the incidence rate on the small area is equal to "F" per unit area. This proposition is easily proved but is well known so that the proof will not be presented here.

The behavior of the gauge under uniform outgassing conditions in a spherical chamber can be explained with the aid of Figure 10. In Figure 10, a section of the chamber wall is shown with the gauge and baffle mounted in it. In order to picture the gauge in a convenient size, the scale has been distorted considerably from what it would be in a large simulator. It will be assumed that in an actual application the dimensions of the gauge and baffle are small relative to the curvature of the chamber wall, and the baffle does not provide significant masking of the wall area near the gauge. The gauge is intended to sense gas emission from the areas A_1 and A_2 on the chamber wall. The chamber is assumed to be spherical and the baffle circular so that areas A_1 and A_2 have circular boundaries. It will be noted that gas originating on surface A_1 enters the gauge by way of the baffle A_3, whereas gas originating on surface A_2 enters the gauge directly. We therefore consider the areas A_1 and A_2 separately. In actuality, the boundaries of zones A_1 and A_2 overlap, but considering the scale, this overlap may be assumed negligibly small. Taking the outgassing rate of the chamber wall to be "F" per unit area, area A_1 can be replaced by the equivalent hemispherical area A_1' with a gas emission rate of "F" per unit area by the first proposition. The incidence rate on the baffle A_3 is then equal to "F" by the second proposition and hence the gas emission rate from the baffle is "F" per unit area. According to the first proposition stated above, the baffle may in turn be replaced by area A_3' with a gas emission rate of "F" per unit area. That is, the incidence rate on the mouth of the gauge due to reflection from baffle A_3 is the same as would be received by the gauge if A_3 were replaced by an area A_3' having the outgassing rate "F." The incidence rate on the mouth of the gauge from area A_2 may be treated similarly. This incidence rate is equivalent to that obtained by replacing A_2 with area A_2' having the same outgassing rate "F." The equivalent areas A_2' and A_3' together define the total gas incidence rate on the mouth of the gauge and also form a complete hemisphere outgassing at a rate "F" per unit area. Thus it follows that the incidence rate on the mouth of the gauge is simply "F" per unit area. With a tubulated gauge as shown, the reading will then be proportional to the gas emission per unit area of the portion of the wall desired.

Next, the more complicated case of non-uniform gas emission from the portion of the wall viewed by the gauge will be considered. It will be seen below that the gauge is more sensitive to a localized gas source near the center of its viewing area than one which is near the periphery. It is the purpose of this section to evaluate the variation in sensitivity over the area viewed. In order to accomplish this evaluation, consider the geometry shown in Figure 11. Here "a" is a portion of the area viewed by a gauge located at O. Gas incidence reaches the gauge by way of the baffle in this case. Entrance plane of the baffle is located at O as shown. The local sensitivity will be expressed in terms of the percentage change in the area "a." The flux on the plane area at O is given simply as

$$\phi = F \sin^2\theta \tag{22}$$

where the gas emission is uniform over the area "a." This expression can easily be derived by substituting for "a" an equivalent spherical surface centered at O. The derivation of this expression will not be included here. The area "a" is

$$a = 2\pi R^2(1-\cos\beta) \tag{23}$$

The angles β and ϕ are related by "equation (24)."

$$\sin^2\theta = \frac{\sin^2\beta}{1-2\frac{r}{R}\cos\beta+(\frac{r}{R})^2} \tag{24}$$

The rate of change of flux with respect to area can then be evaluated as

$$\frac{d\phi}{da} = \frac{d\phi}{d\beta}\frac{d\beta}{da} = \frac{\frac{d\phi}{d\beta}}{\frac{da}{d\beta}}$$

$$= F\,\frac{2\left[(\frac{R-r}{R})^2+\frac{2r}{R}(1-\cos\beta)\right]\quad \sin\beta\cos\beta-2\frac{r}{R}\sin^3\beta}{2\left[(\frac{R-r}{R})^2+\frac{2r}{R}(1-\cos\beta)\right]\quad {}^2\pi R^2\sin\beta} \tag{25}$$

The sensitivity is defined as

$$\sigma_1 = \frac{\pi R^2}{F}\frac{d\phi}{da} \tag{26}$$

That is, "σ" is the normalized flux received from a small area at an angle "β." Then

$$\sigma_1 = \frac{\left[(\frac{R-r}{R})^2+\frac{2r}{R}(1-\cos\beta)\right]\quad \sin\beta\cos\beta-\frac{r}{R}\sin^2\beta}{\sin\beta\quad\left[(\frac{R-r}{R})^2+\frac{2r}{R}(1-\cos\beta)\right]^2} \tag{27}$$

which reduces to

$$\sigma_1 = \frac{\frac{m^2}{k}\cos\beta-(1-\cos\beta)^2}{k\;\frac{m^2}{k}+2(1-\cos\beta)\quad{}^2} \tag{28}$$

where $k = \frac{r}{R}$, $m = 1-K$.

"Equation (28)" applies to the gas incidence rate on the baffle. This fact can be seen by a comparison of Figures 10 and 11; the gas incident on the baffle in Figure 10 corresponds to that incident on the surface at point O in Figure 11. Because the baffle is small this incident flux will be uniformly distributed on the whole surface of the baffle, and a portion of it will be reflected to the mouth of the gauge. The flux on the mouth of the gauge will, in fact, be

$$\phi = F_B \sin^2\beta_B \tag{29}$$

where F_B = the flux per unit area leaving the baffle.

β_B = one half of the plane angle subtended by the baffle at the mouth of the gauge.

Since $F_B = \phi_B$ = the incident flux on the baffle,

$$\sigma_G = \frac{R^2}{F}\frac{d\phi_G}{da} = \frac{R^2}{F}\frac{d\phi_B}{da}\sin^2\beta_B = \sigma_1 \sin^2\beta_B \tag{30}$$

That is, the sensitivity calculated above for incidence on the baffle must be multiplied by the factor "$\sin^2\beta_B$" when applied to incidence on the gauge itself for gas flow reaching the gauge by way of the baffle.

The remainder of the gas incident on the gauge comes from that portion of the wall in direct view from the gauge mouth, area A_2 in Figure 10. The calculation of sensitivity in this zone is approached in the same manner as the preceding. Referring to Figure 12, the gauge mouth is located on plane O and views a band on the chamber wall designated as A_2. Remembering that the local sensitivity relates to a small zone in area A_2, it can be seen that the local sensitivity in the situation depicted in Figure 12 will be described by the same equation as that in Figure 11 except that "r" is replaced by "-r" and "$\cos\beta$" is replaced by "$\cos(180-\beta)$" or "$-\cos\beta$." That is

$$\sigma_2 = \frac{(1-\cos\beta)^2 - \frac{m^2}{k}\cos\beta}{k\left[\frac{m^2}{k}+2(1-\cos\beta)\right]^2} \tag{31}$$

It will be of interest to evaluate these expressions and observe the variations in "σ" that appear in a typical case. Let us assume that the following dimensions are typical of a large simulator:

R = radius to chamber = 100 ft
Wall to baffle distance = 2 ft
Wall to end of gauge tubulation = 1.8 ft

Then

for baffle: $k = 0.98$, $m = 0.02$

for gauge tube: $k = 0.982$, $m = 0.018$

Let us assume further that the total area viewed by the gauge is one twelfth of the chamber wall. Then the central angle "β" has a maximum of 33.3° and β_B is approximately 73.3° so that the correction factor for baffle readings is:

$$\sin^2\beta_B = 0.91 \tag{32}$$

The local sensitivity varies with the angle "β" as shown in Figure 13. This result indicates whether the gauge reading is a reasonable average of the wall outgassing rate. It is seen that the average is highly weighted in favor of gas emission in the immediate vicinity of the gauge. This behavior is undesirable for measurements in a chamber because a local gas source appearing in the area monitored by the gauge is likely to fall in a region where the sensitivity will differ considerably from the average. The leak will then be given considerably more or less weight than it deserves. Or, to put it another way, the gauge will not register the average gas emission rate to be applied to the area viewed.

3.3 APPLICATION OF THE TYPE 2 GAUGE

The Type 2 Space Simulation gauge is designed to obtain the pattern of gas emission from the wall of a space simulation chamber by using a number of gauges, each viewing a restricted area. Its ability to perform in this way is subject to certain limitations discussed above. Assuming that these limitations can be satisfied, the data obtained must be converted to incidence rates on the vehicle. In order to make this conversion, it is necessary to perform a set of mathematical calculations. These calculations involve not only the gas emission pattern, but the shape and size of the vehicle.

There are at least two approaches to this analysis, or perhaps it should be called synthesis, of the data. The first approach is based on considering the wall to be divided into equal circular areas corresponding to the faces of a regular polyhedron or Platonic solid. Gas emission from each of these areas is measured with one or more gauges. Suppose there are twelve such areas corresponding to the faces of a dodecahedron. The flux on a spherical vehicle may be calculated at twelve points corresponding to these faces in a rather simple manner. Any such point will be receiving gas from all or part of six zones on the wall. The flux from a zone directly above the point can be calculated easily in the same manner as the flux on the baffle was calculated in the preceding section. The ratio of the flux incident on the vehicle to that emitted from the wall yields a probability P

$$\frac{\phi_1}{F_1} = P \tag{32}$$

that a molecule arriving at the vehicle has originated in the zone directly over the point. The probability of a molecule coming from the other five visible zones is then 1-P, and the probability from any one zone is $\frac{1}{5}$ (1-P). The flux from any other zone is

$$\phi_2 = \frac{F_2(1-P)}{5} \tag{33}$$

When more than twelve zones are used, the analysis is more complicated. In particular, the number of zones visible at the point on the vehicle must be evaluated carefully. It may be necessary to figure a probability for one set of off-axis zones. The calculation would be performed in the same way but would, of course, yield values at more points on the vehicle.

The second approach to the problem makes use of the mathematical study of gas distribution of C. Tsonis previously mentioned. In this case the chamber wall is divided into band-like spherical zones with a common axis passing through the point in question. Gauge readings are then interpreted as gas emission per unit area and those falling in a given band are averaged. The probability or transfer function from each band is then obtained from the mathematical study and applied as a multiplier to the average gas emission measured in that band. The results, when summed, give the incidence rate on the vehicle at the point. This technique requires much more extensive calculation than the former but provides data at any desired point on the vehicle. It has a further advantage in that overlap of the areas viewed by gauges is not objectionable, but at the same time, a large number of gauges are required.

The Type 2 gauge has certain desirable features for this type of application. It is independent of effects of the outgassing pattern or pumping pattern in the chamber provided the cosine distribution is applicable. It is independent of pumping coefficients of the various gas constituents. The Type 2 gauge is also independent of gas temperatures, but the gauge itself does have to be maintained at a known temperature. The measurement is obtained in terms of molecular incidence rate and can be used to calculate incidence rates on a test vehicle.

Disadvantages also appear in the Type 2 configuration. Outgassing of the walls and baffle of the gauge may contribute significant amounts to the pressure readings; running these surfaces at elevated temperature is therefore recommended. The variation of sensitivity over the viewing area has already been mentioned. This effect might be reduced by addition of a secondary baffle partly obscuring the zone of high sensitivity. In addition, gauge locations involving a known discontinuity in the wall characteristics near the extremes of the area viewed should be avoided. The mathematical calculations involved in the interpretation of the data constitute a further disadvantage of this type of gauge. This type of gauge is further limited to spherical or nearly spherical test chambers.

The space simulation gauge, then, makes it possible to measure incidence rates on a test vehicle with fixed, wall-mounted gauges.

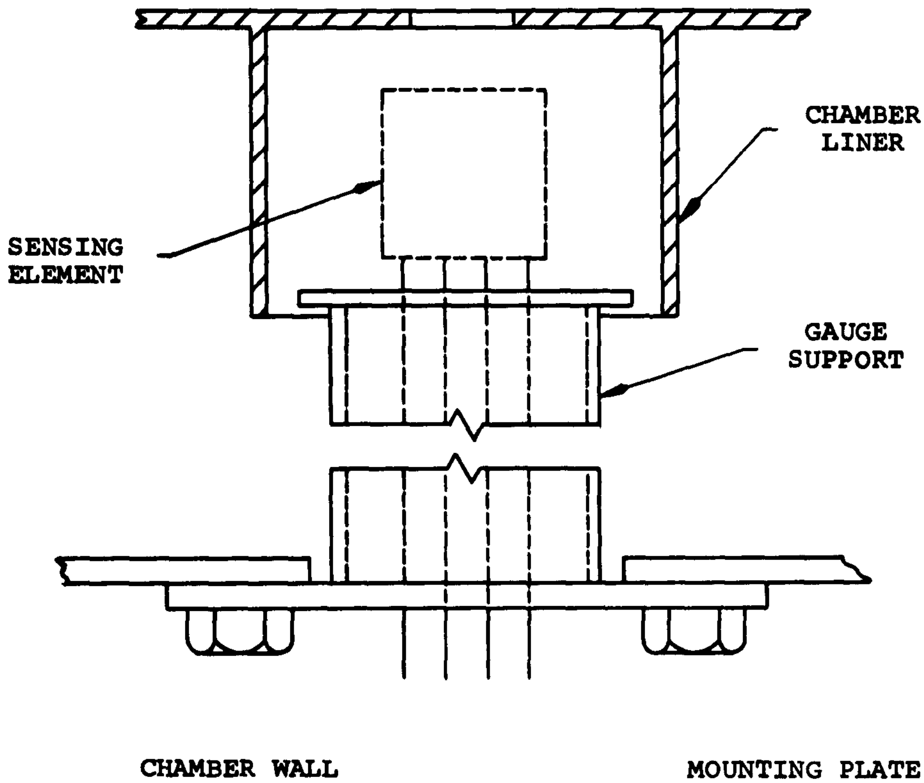

Fig. 1 Space Simulation Gauge – Type 1

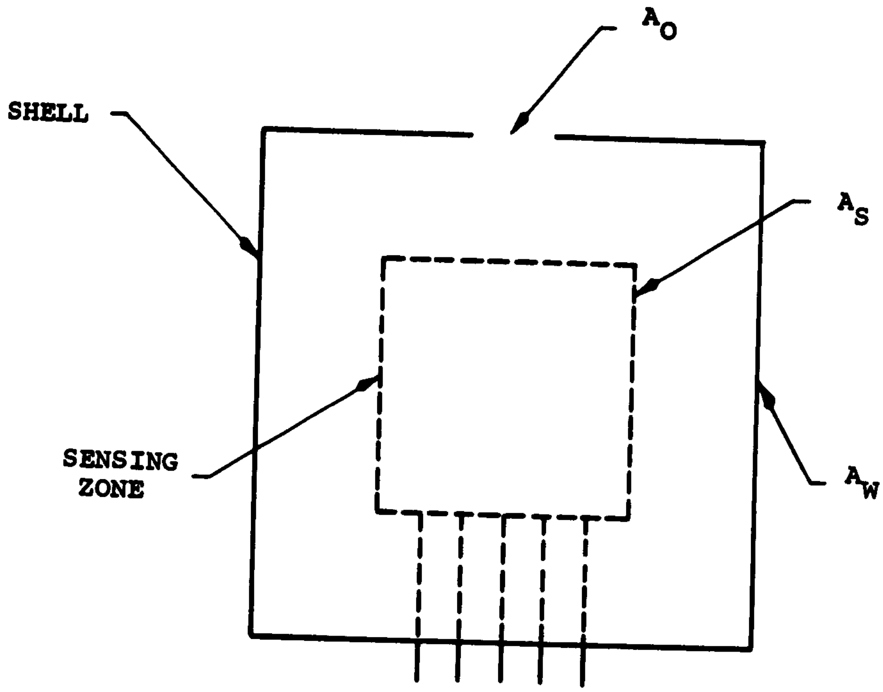

Fig. 2 Conventional (Non-Pumping) Gauge

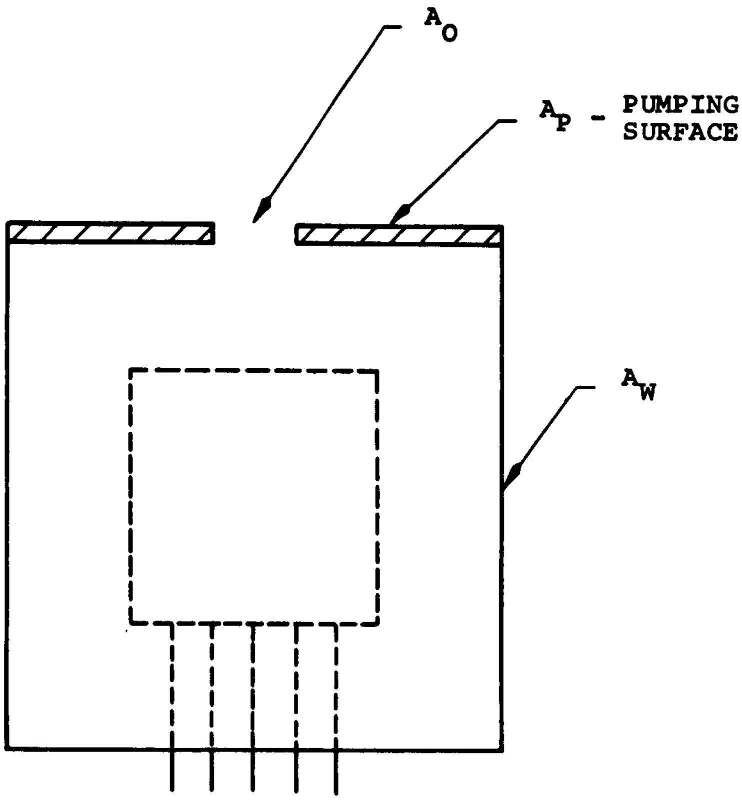

Fig. 3 Basic Pumping Gauge

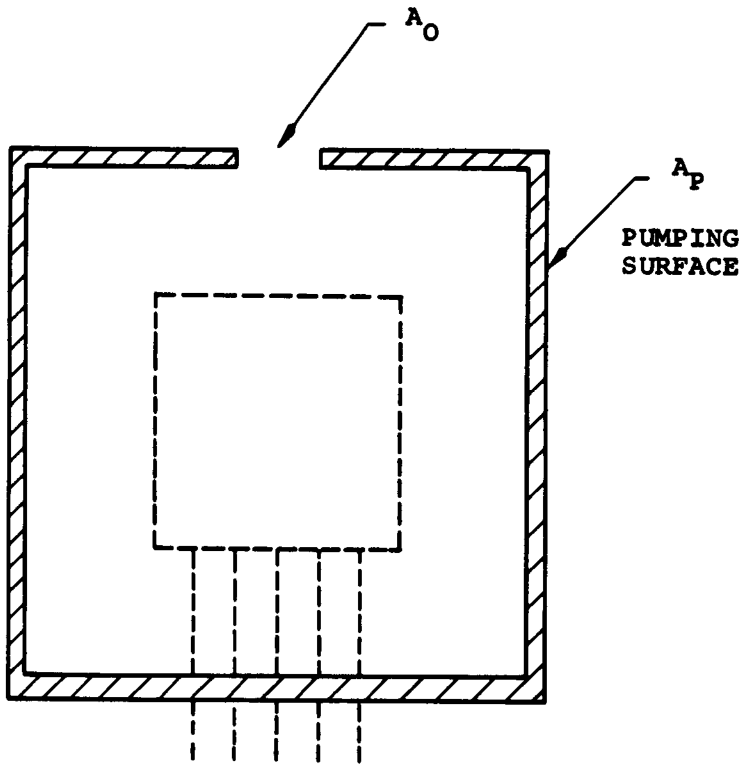

Fig. 4 Fully Pumping Gauge

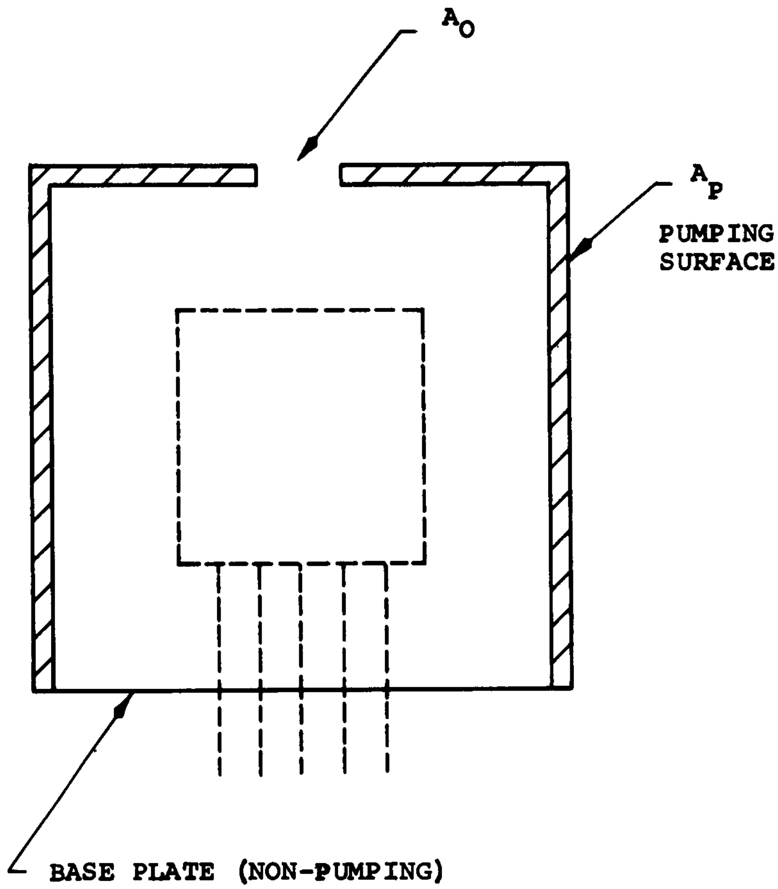

Fig. 5 Pumping Gauge with Uncooled Base Plate

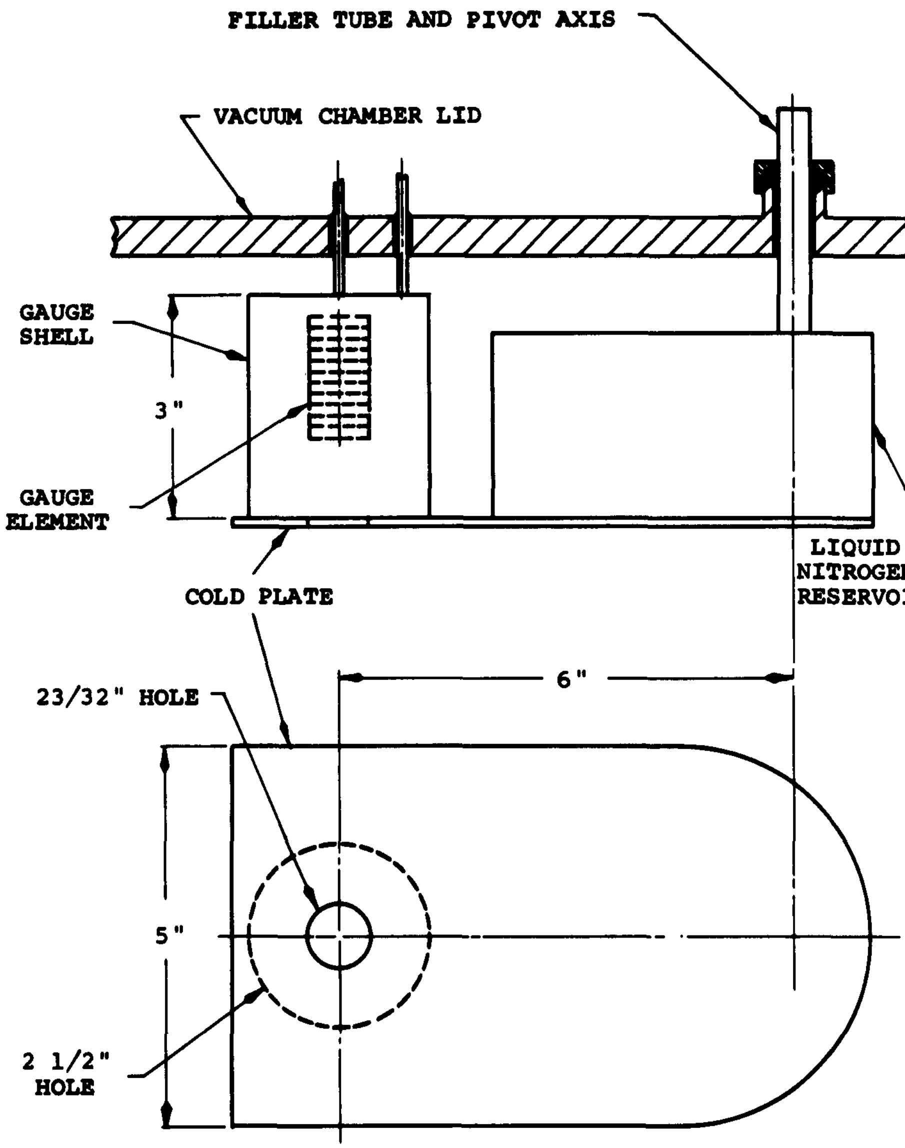

Fig. 6 Experimental Space Simulation Gauge

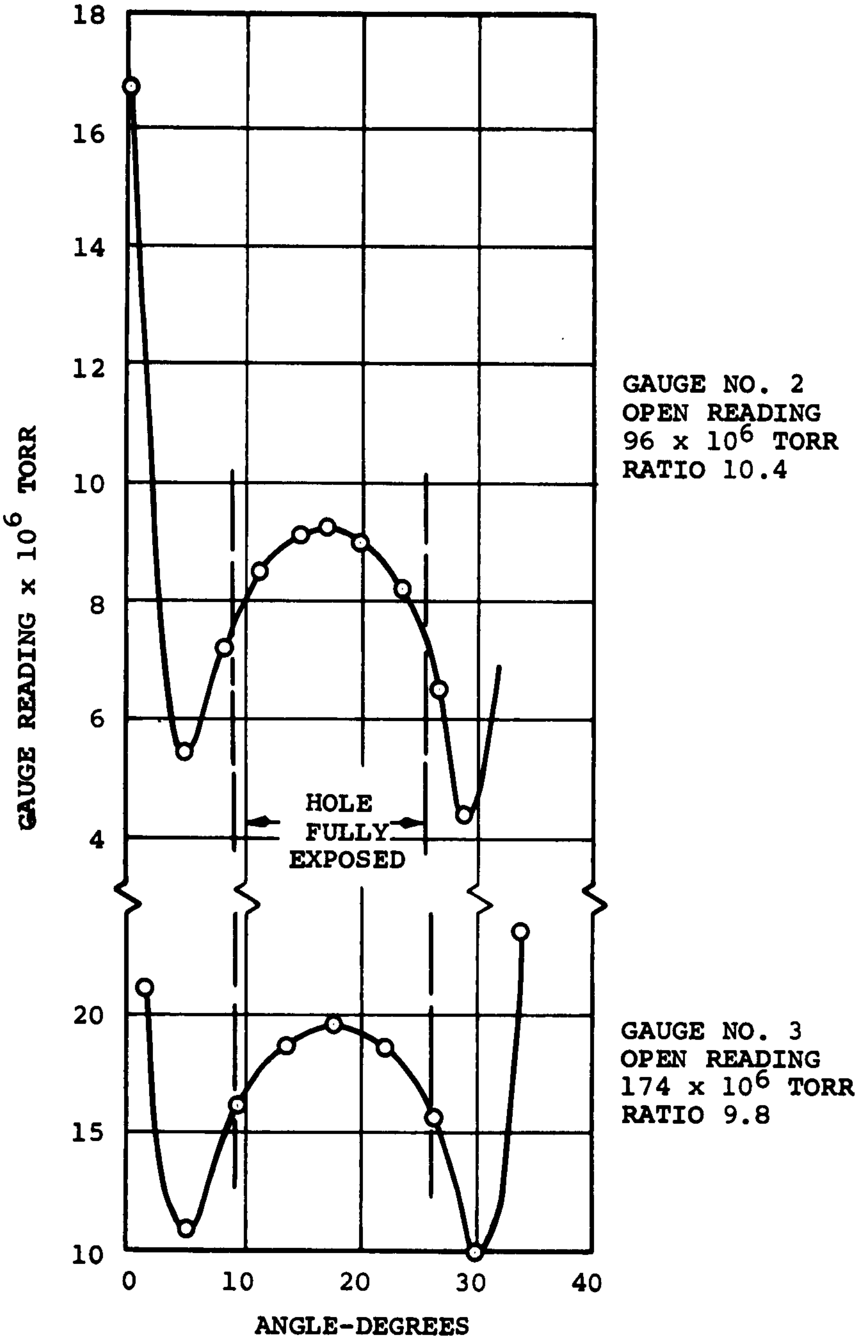

Fig. 7 Space Simulation Gauge Characteristics

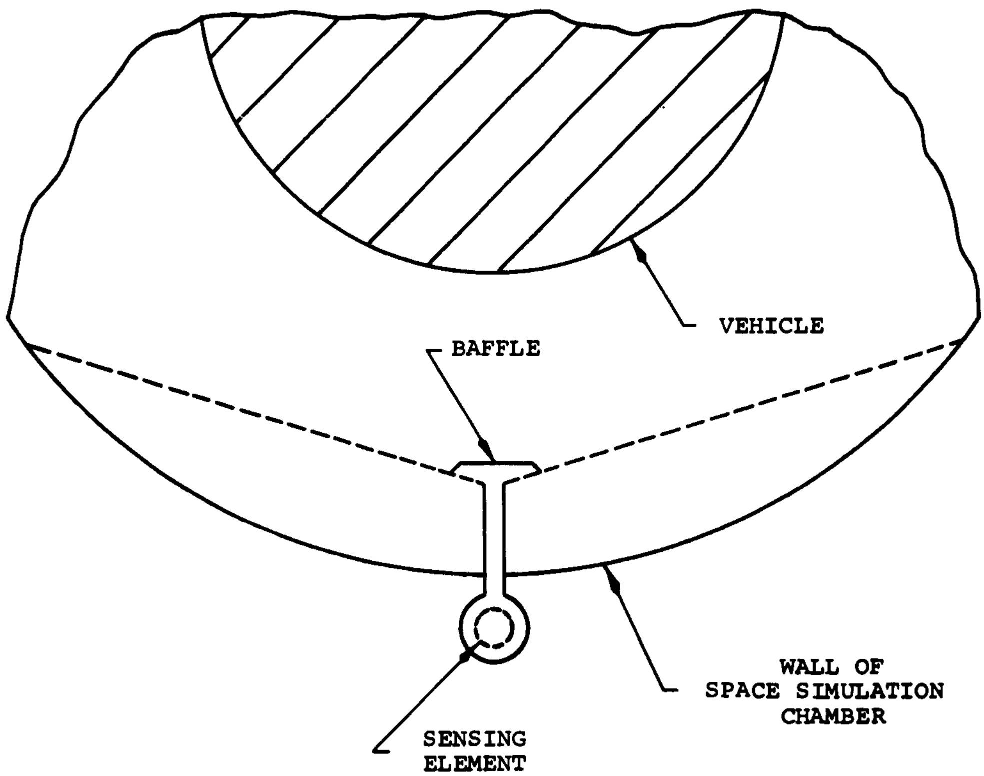

Fig. 8 Type 2 Space Simulation Gauge

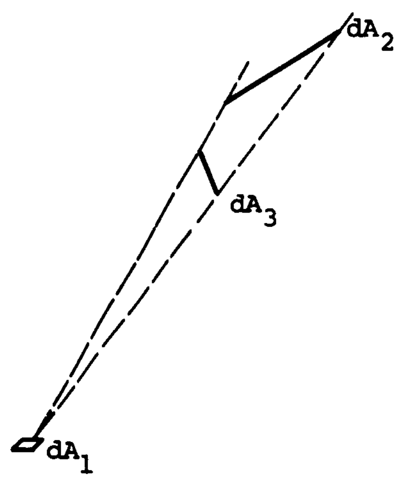

Fig. 9 Equivalent Areas

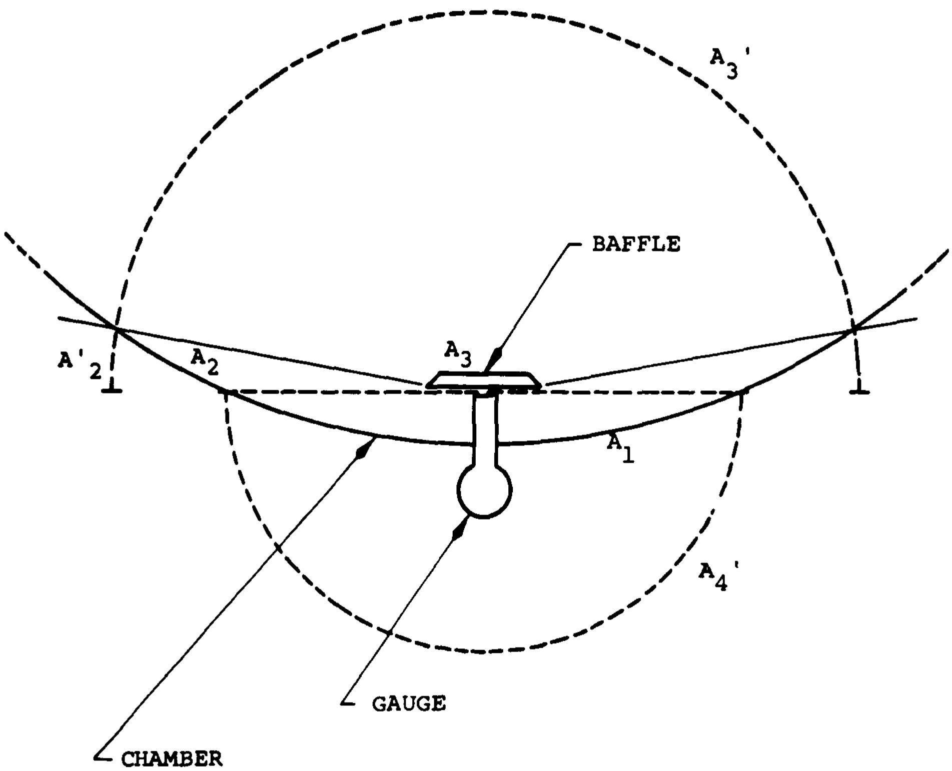

Fig. 10 Gas Incidence on Gauge

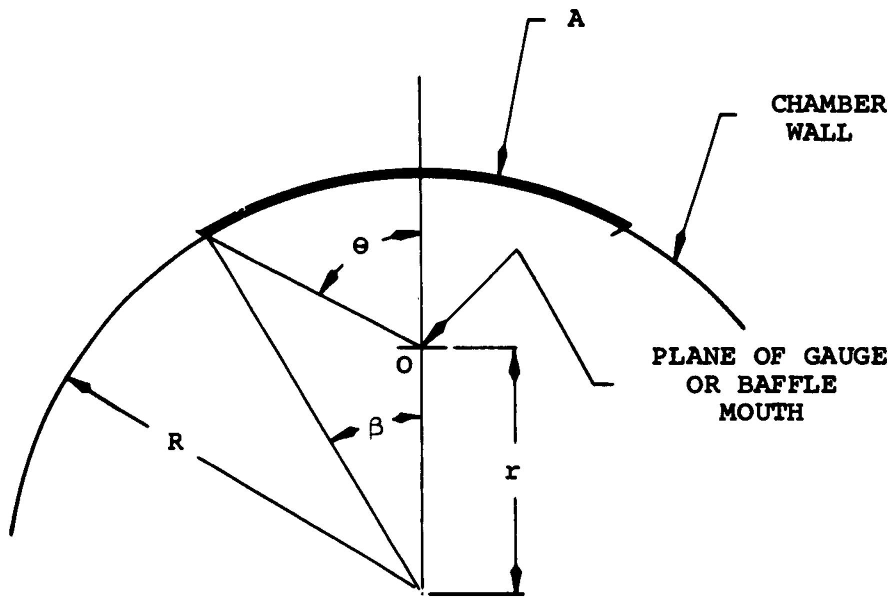

Fig. 11 Computation of Local Sensitivity

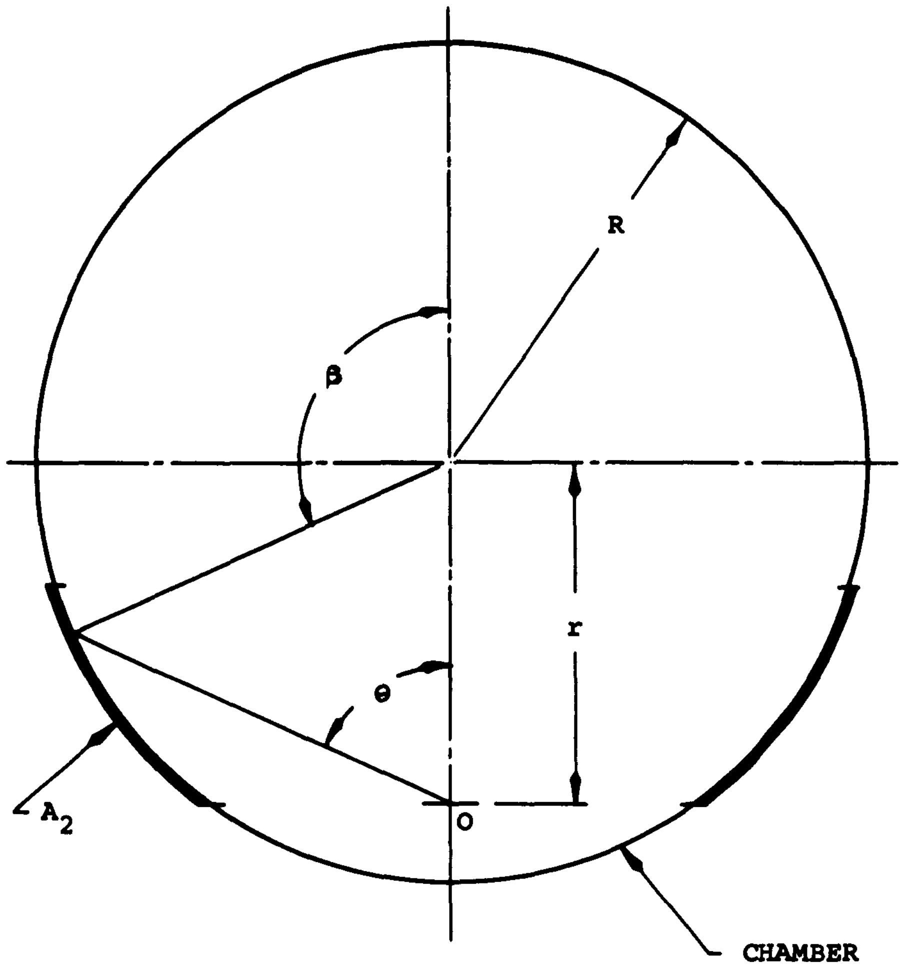

Fig. 12 Computation of Local Sensitivity – Area A_2

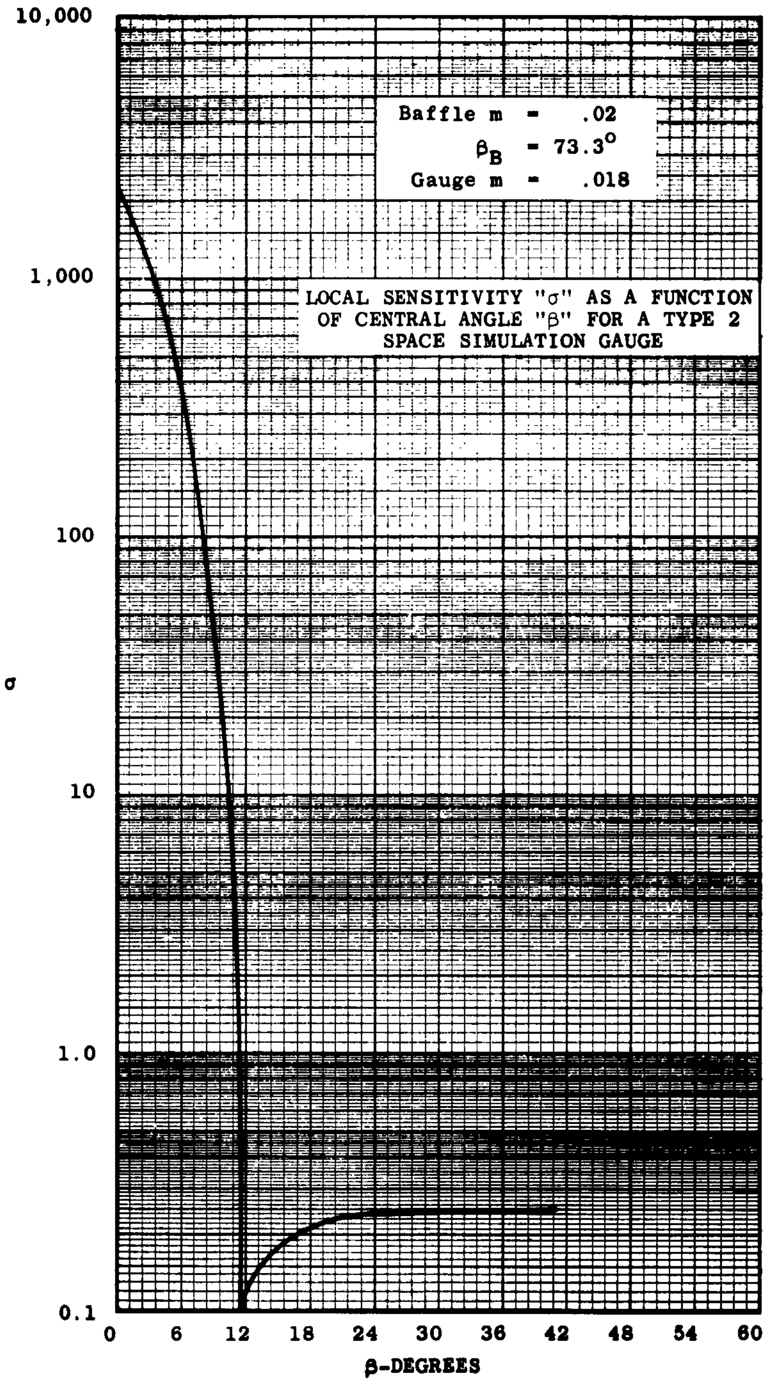

Fig. 13 Local Sensitivity

Arnold Engineering Development Center
Arnold Air Force Station, Tennessee
Rpt. No. AEDC-TDR-63-148. SPACE SIMULATION GAUGES. July 1963, 41 p. incl 13 refs., illus.

Unclassified Report

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1. Space environmental conditions
2. Test facilities
3. Instrumentation
4. Meters
5. Sensitivity
6. Cryogenics

I. AFSC Program Area 850E, Project 7778, Task 777801
II. Contract AF 40(600)-954
III. Aero Vac Corporation, Green Island (Troy), New York
IV. Holkeboer, David H.
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